433 Eros Landing – Development of NEAR Shoemaker's Controlled Descent Sequence

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Abstract

On February 12th, 2001, the NEAR Shoemaker spacecraft made its historic descent to the surface of the asteroid 433 Eros, becoming the first spacecraft to soft land on a small celestial body. Development of the final descent activity offered the NEAR team a difficult technical challenge as the spacecraft had been designed solely as a free flyer, not as a lander.

The NEAR Shoemaker spacecraft rendezvoused with 433 Eros on February 14th, 2000. Following an intensive year of orbital operations collecting science data at decreasingly lower altitudes, the spacecraft was prepared to conduct its final activity, descending from its current 36 km orbit in a series of five propulsive maneuvers to land on the surface of 433 Eros. As a free flyer, the spacecraft's orbital operations were extremely successful, collecting an order of magnitude more images of the asteroid's surface than originally planned. However, since the spacecraft was not designed to be a lander, landing presented a whole new challenge to the Navigation, Mission Design, Guidance and Control, and Mission Operations Teams.

This paper discusses the development of the controlled descent sequence from an operations perspective, focusing on the inherent difficulties of performing an activity for which the spacecraft was not originally designed, and the way in which these challenges were overcome by the NEAR team.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission, sponsored by the National Aeronautics and Space Administration (NASA), was the first mission to be launched in NASA's "better, faster, cheaper" Discovery Program[1,2]. Built and operated by the Johns Hopkins University Applied Physics Laboratory (JHU/APL), NEAR was the first scientific mission dedicated to the comprehensive study of an asteroid. Launched from Kennedy Space Flight Center on February 17th, 1996 aboard a Delta II-7925 launch vehicle, NEAR Shoemaker began an extended cruise phase journey to the asteroid 433 Eros. While en route, the spacecraft performed the first reconnaissance of a C-type asteroid during a close flyby of the main belt asteroid 253 Mathilde on June 27th, 1997. Carrying an instrument suite consisting of a multispectral imager (MSI), near infrared spectrograph (NIS), X-ray/gamma ray spectrometer (XGRS), laser rangefinder (NLR), and magnetometer (MAG), the spacecraft was inserted into Eros orbit on February 14th, 2000. During the subsequent year of orbital phase operations at progressively lower altitudes, the spacecraft performed in-depth scientific measurements of the asteroid's surface composition, geology, physical properties, and internal structure, collecting an order of magnitude more science data than originally envisioned. The orbital mission phase culminated on February 12th, 2001 with a controlled descent and soft landing on the surface of Eros. Although landing on Eros was defined as the end of mission, the phenomenal success of this activity resulted in a two week mission extension. Remarkably, the NEAR Shoemaker spacecraft was designed as a free flyer and was ill-suited to the role of lander. This paper discusses the challenges encountered and overcome by the NEAR Mission Operations team in designing and implementing this historic touchdown.

DESCENT SEQUENCE OBJECTIVES

The controlled descent and soft landing activity was conceived to satisfy two goals. The primary goal was to acquire high resolution images of the asteroids surface to help answer the many lingering questions the NEAR science team had about Eros. During a series of low altitude flyovers in late January 2001, the minimum image distance achieved was 2.7km. The goal of the controlled descent was to acquire images down to a 500m altitude, providing a resolution of approximately 10cm. The second goal was a flight demonstration of a controlled descent to a small body. To satisfy this goal, an impact velocity less than 3m/s was specified. An ancillary objective was to acquire a post touchdown communications beacon from the spacecraft to confirm landing survival. Since the NEAR spacecraft did not incorporate a landing gear, this latter objective was ambitious.

DESCENT SEQUENCE OVERVIEW

For several months prior to the controlled descent, the Navigation, Mission Design, Guidance and Control, and Mission Operations teams worked with the Mission Director to design a controlled descent and soft landing sequence compatible with spacecraft capabilities. Eventually, a series of five propulsive maneuvers was identified which presented the best chance for achieving the goal of the descent activity: high resolution images of the asteroid. A detailed description of the descent design is presented by Antreasian et al[8]. These five delta-v burns were identified as End of Mission Maneuvers (EMM) and labeled EMM-1 through EMM-5.

Commencing from a circular 36 km 176 degree inclination orbit, EMM-1 moved the spacecraft to a 36 km x 7 km elliptical orbit with 135 degree inclination and perigee over the mid-southern latitudes near the nominal impact point[12]. Approximately 2 hours after EMM-1, EMM-2 executed near perigee, placing the spacecraft in a nearly vertical trajectory. Although these burns were essential to the controlled descent, spacecraft constraints prevented simultaneous science data collection and high rate telemetry retrieval during their execution. However following EMM-2, subsequent propulsive maneuvers, EMM-3 through EMM-5, were designed to allow continuous high-gain antenna communication with

Earth while simultaneously pointing the instrument axis generally in the nadir direction while at burn attitude. Acquisition and transmission of MSI images, NLR ranges and spacecraft housekeeping began shortly after EMM-2 burn completion and continued uninterrupted through touchdown.

DESCENT SEQUENCE IMPLEMENTATION

Data Management

The primary goal of the controlled descent and soft landing was to collect high resolution images of the asteroid at altitudes down to 500 meters. Since there was no guarantee that the spacecraft would survive touchdown, minimum latency between image collection and retrieval was paramount to success. Even if the spacecraft was viable after touchdown, it would be impossible to aim the rigidly mounted parabolic high gain antenna at Earth while resting on the surface of a rotating asteroid. Alternatively, downlink bandwidth available from the low gain and medium gain antennas would be insufficient for image recovery. Consequently, a technique for simultaneously collecting and transmitting science data in realtime with minimal latency was necessary.

While NEAR had the capability to route science data from the imager to the realtime data stream via the 1553 bus, this was a rather slow process requiring in excess of nine minutes to transmit a single uncompressed image. With the science collection portion of the descent sequence spanning only forty five minutes, this method would not support the data volume desired by the science teams and a closest image altitude of 500 meters would be unachievable.

Abandoning this approach, Mission Operations analysts resorted to an "optimized" implementation of the normal data storage and retrieval technique used throughout the orbital mission phase. This technique routed MSI images to the onboard Solid State Data Recorders (SSRs) via a dedicated high speed link, while simultaneously collecting NLR ranging, high rate spacecraft housekeeping and attitude history packets via the Command and Telemetry Processor (CTP) 1553 data bus. Since operational constraints prevented simultaneous read/write operations on a single recorder these data were forwarded to redundant SSRs that alternated between record and playback on an autonomy driven sixty five second schedule. Using this technique, SSR1 would record two MSI images plus ancillary telemetry for sixty five seconds while SSR2 played back the previously recorded data to the ground. Both recorders would then alternate their functions; SSR2 would record while SSR1 played back its data and then the cycle would repeat. Because command memory space was a precious resource, commanding of this record/playback cycle was performed by the onboard autonomy system. Beginning shortly before EMM-2, this cycle continued well past the expected touchdown time. The sixty five second duty cycle was chosen after careful analysis, balancing the amount of data recorded vs the time needed to play it back to the ground. Additionally it was observed throughout the mission that the first couple of seconds of playback data was lost while the ground system synchronized to the playback stream. To protect the data against this possible loss, images were timed to occur several transfer frames into the record session. Additionally, SSR record sessions overlapped by two seconds to prevent data loss from ground system synchronization delays.

Image Quality

The technique for collecting and recovering descent images had been resolved, but there were still concerns regarding image quality. A fundamental requirement for EMM-3 through EMM-5 was to allow continuous high-gain antenna communication with Earth while simultaneously pointing the MSI boresight at Eros. Unfortunately, burn attitudes varied in roll about the +Z-axis, sometimes to a great extent. When commanded to a new attitude, the NEAR Guidance and Control system transitions as rapidly as possible. Left unregulated, nominal angular rates encountered while slewing between maneuver attitudes would be sufficient to smear MSI images. NEAR analysts resolved this problem by substituting commands to perform a scan pattern in place of the normal attitude commands. The scan pattern allowed a slew rate to be specified which would prevent image smearing and leave the spacecraft close enough to the desired burn attitude that a subsequent traditional attitude command could quickly bring the spacecraft to the correct attitude prior to maneuver execution.

Maneuver Implementation

During the orbital phase of the mission, NEAR executed twenty five Orbit Correction Maneuvers for which Mission Operations analysts had developed a parameterized reusable canned activity sequence. It became evident early in the descent planning that this "tried and true" sequence could not satisfy the unique requirements of the final four descent maneuvers. Amongst these requirements was the need to perform these last four maneuvers within a forty five minute interval. This necessitated extensive alterations to the nominal lengthy maneuver setup and cleanup portions of the sequence. For example: Catbed heaters which were normally enabled ninety minutes before a maneuver and disabled immediately prior to burn execution were warmed up as usual prior to EMM-2 but were then left disabled for subsequent maneuvers. Nominally the rate and type of telemetry collected by the SSR during a maneuver was routinely changed throughout the different portions of the burn sequence. However in this case, due to the careful balancing of telemetry rates required by the special data record/playback scheme, these selections were commanded in the initial setup of EMM-2 and left unchanged throughout the ensuing sequence. Sequencing to re-start accelerometer bias estimation following burn execution was omitted in latter descent maneuvers since there was insufficient time to re-compute a new bias estimation between burns; the bias computed prior to EMM-2 was used for all subsequent maneuvers. Fuel tank valves that were normally closed following maneuver execution were left open for the entire descent following EMM-2.

Normally thrusters are responsible for attitude control during propulsive maneuvers and reaction wheels acquire responsibility upon burn completion. However, NEAR's reaction wheels lacked the necessary control authority to maintain attitude control upon touchdown. Therefore, to mitigate the consequences of an early touchdown, thrusters retained attitude control responsibility following the execution of EMM-4. This responsibility continued through EMM-5 and was not relinquished until the nominal touchdown time plus fifteen minutes, when Guidance and Control subsystem actuators were turned off. Commands were also injected into the sequence following EMM-4 to mask downward firing thrusters during intervals of thruster attitude control. These modifications resulted in unique instantiations of the burn sequence for each of the final four descent maneuvers.

Autonomy

In the event of a significant spacecraft anomaly, the NEAR autonomy philosophy was to safe the spacecraft and wait for ground intervention to correct the problem. In accordance with this philosophy, critical fault detection resulted in spacecraft mode demotion and reconfiguration that disabled the time-tag checking process. Realizing that once EMM-1 executed, NEAR would be on an impact trajectory with Eros, spacecraft mode demotion would be catastrophic. The only chance of successfully soft landing the spacecraft was to faithfully execute the planned time-tag command sequence. Following a thorough analysis of autonomy rules and interactions, the command processor's autonomy state was reconfigured to prevent safe mode demotion during descent. Additionally, to prevent the Flight Computer from independently demoting mode, many of its internal data structures were loaded with increased limits. Autonomy rules that detected and corrected non-critical faults were left enabled since their execution would not precipitate spacecraft mode demotion.

As originally designed, the autonomy system response to an instrument disaster flag was to turn the offending instrument off. Since turning the MSI or NLR off served no useful purpose during the final descent, instrument disaster rules were disabled for this end of mission activity.

To protect the NLR during orbital operations, autonomy rules monitored the diode pump temperature and automatically disabled lasing if a maximum temperature was exceeded. Similarly, before lasing was enabled, autonomy checked the diode pump temperature and only proceeded with the fire enable command if thermal limits were satisfied. Obviously, these safeguards served no useful purpose during the final descent activity. Since NLR autonomy rules could not be easily circumvented without impacting the command scheduling system, they were redefined to prevent thermal limits from affecting NLR fire enable commands.

Power Management

Although power management during the controlled descent was paramount to success, it was never a major concern. Since the XGRS and NIS were not required for this activity, they were turned off to conserve power prior to commencing the initial descent maneuver. A key element designed into the sequence for monitoring descent progress was the operation of the NLR. With the NLR producing realtime range measurements during the descent, ground observers would be able to more accurately gauge how closely the landing maneuvers followed the predicted descent profile. While lasing throughout the braking maneuvers was clearly desirable from this perspective, it had been a longstanding power constraint not to fire the NLR concurrent with the thrusters. After carefully analyzing power margins, it was decided that concurrent NLR lasing would be possible if the propulsion system catbed heaters were disabled. Since intra-burn intervals for the final four maneuvers were minimal, disabling the catbed heaters during this interval was acceptable to the propulsion system engineer. Consequently, upon completion of EMM-2, the catbed heaters were permanently disabled and NLR lasing was enabled for the remainder of the descent.

DESCENT RESULTS

On February 12th, 2001 the controlled descent and landing sequence commenced with EMM 1 execution @ 15:13:56 UTC and terminated on the surface of Eros with EMM 5. The final four EMMs began at 18:58:35 UTC with EMM 2, after which subsequent maneuvers were performed approximately every 15 minutes until EMM 5 terminated having successfully soft landed NEAR Shoemaker on the surface of 433 Eros. Landing velocity was approximately 1.7 m/sec and a RF carrier beacon from the surface was immediately received. Later that evening, realtime telemetry was received from the spacecraft confirming its excellent state of health. All subsystems were nominal and the Power Subsystem's solar arrays were generating 5 times more power than spacecraft loads required.

The primary goal of this activity was to collect high resolution images of the asteroid at altitudes down to 500 meters with image resolutions of 10 cm. Shortly after EMM-2, image collection commenced and a total of sixty nine MSI images were collected. Of these, six images were acquired at altitudes at or below 500 meters. The very last image was taken at 130 meters and had a resolution of 1.4 cm. During transmission of this final image, the spacecraft touched down on the surface of Eros, terminating high rate communication. Consequently, only about three quarters of this image was actually retrieved, but the detail is absolutely incredible.

Success of the landing sequence precipitated an extension to the mission. The landing orientation of the spacecraft pointed the instrument suite directly at the asteroid’s surface. Exploiting this opportunity, the XGRS science team requested, and was granted, two weeks to perform in situ Gamma Ray measurements. Gamma Ray science records and Magnetometer science packets were collected and retrieved during the mission extension.

On February 28th, Mission Operations conducted the final Deep Space Network contact with the NEAR Shoemaker spacecraft. The last XGRS Gamma Ray science records were recovered and final commands to initiate hibernation were transmitted. Just before end of track, spacecraft telemetry was disabled and the active transponder's exciter was turned off. Loss of symbol stream and carrier lock were silent witnesses to the end of the NEAR mission.

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